On the Indoor Thermal Behavior of a Building with Cool Envelope Components

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Abstract

During the last decade, computational fluid dynamic simulation tools have been widely applied for accurately modelling outdoor airflows and local microclimate conditions. In fact, a complete understanding of heat transfer phenomena occurring within the built urban environment is needed to properly predict the energy balance, both on a single-building and on an inter-building scale. In this scenario, several research studies have been carried out to evaluate the impact of local passive solutions on buildings indoor environment, especially by means of dynamic simulation tools. However, only a few investigations were performed by considering the local distribution and spatial variability of the indoor building physics generated by the application of passive cooling strategies.

The present research is aimed at bridging this gap by modelling the indoor thermal environment of a case study prototype building, i.e. square cavity, located in central Italy, by considering indoor heat transfer phenomena. A calibrated and experimentally validated CFD model of the building was elaborated to predict the indoor temperature distribution and profile generated by the application of an innovative highly-reflective cool façade painting and cool roofing membrane on the building envelope, compared to a more traditional “non-cool” envelope finishing. So far, the authors have produced only one work about cool roofs in buildings that concerned sloped roofs in a non-insulated building envelope. Here, we deal with insulated architectures, designed according to the recent energy efficiency regulation, and a combined cool roof and cool façade indoor effect. The experimental validation of the model is carried out by means of experimental data that are continuously monitored both inside and outside the case study building by means of dedicated microclimate and weather stations.

Simulation results were therefore post-processed in terms of (i) indoor temperature and (ii) indoor airflows. Main findings confirmed the huge potentiality of the model in realistically reproducing the indoor behavior of the case study building and therefore the urgent need for a CFD-based approach in investigating thermal-comfort conditions. In fact, a non-negligible and positive impact of the cool building envelope on the local indoor thermal comfort conditions is detected with respect to the more traditional non-reflective component.

1. Introduction

The passive cooling capability of highly reflective building envelope materials and solutions, i.e. roofs, walls, and pavements, has been largely acknowledged over the course of the years (Georgakis et al., 2014).

Such high-albedo solutions characterized also by high thermal emittance have been demonstrated to be very effective, not only in reducing buildings cooling energy requirements and improving the indoor thermal comfort conditions by avoiding summer overheating, but also in mitigating local microclimate events such as urban heat island and heat waves phenomena (Wong et al., 2016; Gracik et al., 2015).

The use of cool envelope solutions like cool roofs can lead up to 125 kWh/year of annual electricity saving and up to an 80 % seasonal energy reduction in temperate climates, with little penalties in winter (Akbari 2003; Akbari et al., 1997). Moreover, indoor air temperature reductions up to 3-4 K in peak summer conditions were detected by applying cool coatings on the roof of residential buildings with a consequent considerable reduction of the discomfort

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Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2018. Building simulation applications BSA 2017. bu,press.
https://doi.org/10.13124/9788860461360

hours within different climate boundary conditions (Synnefa et al., 2007).
Nowadays, many different tools and approaches are available to analyze the impact of the application of cool solutions on both the buildings thermal-energy performance and the urban environment (Corrado et al., 2016; Atzeri et al., 2016), i.e. experimental, analytical, and numerical methods (Pisello et al., 2015; Synnefa et al., 2011; Crawley et al., 2001).
Among such approaches, computational fluid dynamic tools represent a suitable and multifunctional approach to predict the indoor effect generated by the modification of the thermal-optical properties of the building envelopes and urban surfaces in terms of (i) airflow distribution, (ii) air quality, and (iii) temperature field (Yang et al., 2013). More in detail, many research studies focus on the CFD evaluation of the impact of the roof inclination, roof-covering materials, and the geometry of the environment on the internal flow (i.e. laminar or turbulent regimes) and temperature distribution in enclosed spaces (Saha et al. 2010; Basak et al., 2008). Moreover, a huge effort in the use of CFD tools to predict the flow and thermal field in enclosed cavities with different geometrical characteristics, such as attic spaces, is registered (Hasani et al., 1998; Asan et al., 2000; Kamiyo et al., 2010; Pisello et al., 2016), by considering $10^9 \leq Ra \leq 10^{11}$ when turbulence occurs.

2. Motivation

Even if many studies were performed to investigate both numerically and experimentally the impact of passive cool solutions applied to building envelope components, still a few studies, focusing on the combination of different cool technologies, can be found in the literature. Therefore, building upon previous research efforts about (i) cool roof application for improving indoor thermal comfort conditions and (ii) the use of CFD tools to properly describe the indoor airflow and thermal environment of buildings, the present work concerns the CFD numerical analysis of the indoor thermal field and airflow inside a case study prototype building, i.e. test-room. The final aim is to assess the combined effect of the application of two cool envelope solutions, i.e. cool roofing membrane and cool façade painting, when applied on the building envelope. In particular, the CFD was used in order to determine the indoor air temperature spatial distribution profile inside the cavity, by investigating at which height the passive cooling effect of the cool membrane is extinguished. To this aim, a preliminary continuous monitoring of the main indoor-outdoor microclimate parameters was carried out to support the validation and calibration of the numerical CFD model of the building. Therefore, two scenarios were simulated and compared: (i) a more traditional building envelope (standard non-cool surfaces) and (ii) a cool building envelope (characterized by the application of the cool roofing membrane and cool façade painting on the envelope).

3. Description of the Case Study

The case study building consists of a fully instrumented test-room (3.78×3.78×2.85 m) located in Perugia (Italy), and designed according to the recent construction techniques (Pisello et al., 2014a).
Fig. 1 reports the pictures of the roof and the façades of the case study building before (Fig. 1a) and after the application of the cool membrane and reflective painting (Fig. 1b).

Fig. 1 – (a) Cool and (b) standard configuration of the case study building

The reference building is characterized by a rectangular double shutter window with wood frames in the South façade and a rectangular armored door in the North façade, for a global fenestration ratio of about 0.041.
The opaque envelope of the case study building was developed by using an innovative construction stratigraphy in order to be consistent with the Italian regulations in terms of walls' thermal stationary

properties, and representative of a common residential building in Italy. The specific characteristics of the test-room envelope components are specified in Table 1.

Table 1 – Building characteristics in terms of materials and main thermal properties of the envelope

	Material	Thickn. [m]	Th. Cond. [W/mK]	Th. Transm. [W/m²K]
Walls	plaster	0.02	0.50	0.49
	EPS	0.09	0.04	
	brickwork	0.30	0.27	
	plaster	0.02	0.40	
Roof	waterproof membrane	0.01	0.23	0.25
	mineral wool	0.10	0.04	
	concrete slab	0.20	0.16	
	plaster	0.015	0.40	
Floor	cast concrete	0.2	1.13	0.38
	stone wool	0.08	0.04	
	linoleum	0.015	0.17	

All the real thermal properties and characteristics of the building envelope components were used as input data in both models of the building.

More in detail, a simplified building geometry was implemented, by assuming a single solid layer for each building envelope component.

Therefore, the thermal properties of the one-layer simulated configuration were accurately calculated by considering the realistic multi-layer components connected in series.

4. Methodology

The methodology applied consists of the following main steps:

- selection of the proper case study, i.e. prototype test-room;
- continuous monitoring of the main indoor-outdoor microclimate parameters;
- CFD simulation of the summer indoor thermal profile and velocity field generated inside by the application of (i) traditional non-cool materials and (ii) cool highly-reflective envelope materials;
- validation of the model by means of the experimental continuously monitored data;
- post-processing and discussion of the achieved results.
- Therefore, two building scenarios were assessed:
- *Standard configuration*: building envelope covered by traditional non-cool materials;
- *Cool configuration*: building envelope covered by innovative high albedo materials, i.e. cool roofing membrane and wall painting.

The more traditional envelope materials are characterized by an albedo of 19 %, while the innovative cool envelope materials are characterized by a higher albedo i.e. 77 %. In both the building configurations, the building envelope materials present a thermal emissivity of 88 %, as previously experimentally measured (Pisello et al, 2014a; Pisello et al., 2014b).

4.1 Experimental Monitoring Campaign

The purpose of the study is to (i) compare the thermal behavior of the two innovative cool envelope solutions, i.e. cool roof membrane and cool façade painting and (ii) validate the numerical model elaborated. To this aim, the two envelope solutions were applied on the roof and on the differently oriented walls of a prototype case study building, i.e. test-room, located inside the university campus in Perugia, in central Italy. The in-situ continuous monitoring of the thermal performance of the proposed solutions was carried out under real dynamic boundary conditions during the summers of 2014 and 2015. Both the main indoor/outdoor thermal parameters and the roof albedo were monitored.

Firstly, the case study building with non-cool envelope materials, i.e. bitumen membrane and red-colored painting, was monitored as a base case scenario. Secondly, the cool membrane was applied on the test-room roof, in order to assess the specific contribution of the cool roof to the thermal performance of the test-room in summer conditions. Thereafter, the cool painting was applied to the differently oriented façades, i.e. South, North, East, and West facing façades of the same case study prototype building.

In this way, the performance of the coupled solutions was analysed in terms of passive cooling effect. The monitored data were subsequently post-processed to compare the thermal effect of the two cool solutions.

In detail, the following different scenarios for the case study building envelope were identified:

- *Standard scenario* (S): The materials implemented in the building envelope were representative of the solutions commonly used in new buildings in Italy. In particular, the roof is covered with a bituminous black membrane and the walls with a red-colored traditional painting;
- *Cool Envelope scenario* (CE): The innovative cool façade painting is applied on all the façades of the case study building.

In detail, the cool roofing membrane consists of a polyurethane-based waterproof liquid white membrane with high elasticity. The cooling potential of such membrane was optimized through iterative laboratory and in field tests by increasing specific components such as the titanium dioxide (TiO_2) and hollow ceramic microspheres percentage. The final optimized membrane presented almost 12 % of TiO_2 and 4 % of hollow ceramic microspheres.

The proposed cool painting for building façade applications consists of an almost white non-organic painting, mainly composed by potassium silicate with a small percentage of resin. It is characterized by high vapor permeability.

Also the painting was optimized through an iterative procedure by increasing TiO_2 and the hollow ceramic microspheres' percentage.

The most performing combination was found to be again with 12 % of TiO_2 and 4 % of hollow ceramic microspheres.

4.2 Elaboration of the Model

In order to compare the effect of cool envelope materials on (i) the indoor air temperature distribution and (ii) indoor airflow of the case study prototype building, a two-dimensional finite element CFD analysis was performed. Two different 2-d models were elaborated and compared, i.e. referring to the standard and cool configuration of the case study building, respectively. The simulations were performed in transient conditions by considering one representative summer day selected from the experimental monitoring campaign previously described. Moreover, the simulation was reiterated by using each time, as input values, the final outputs from the previous simulation in order to achieve stability. A simplified scheme of the prototype case study building, i.e. North-South oriented square cavity, was simulated in order to predict the thermal behavior of the building (Fig. 2).

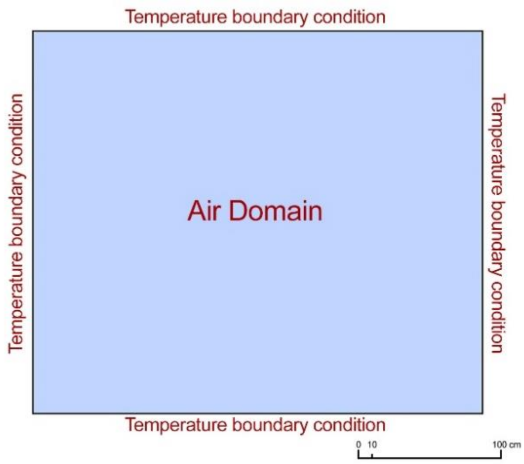

Fig. 2 – Cross section and main dimensions [cm] of the simplified square cavity representing the test-room case study building

The boundary conditions in terms of surface temperatures were set by using experimental measurements monitored in the field, and collected (averaged) every 10 minutes Such measurements were imposed both on (i) the vertical wall and (ii) the horizontal roof. As for the bottom boundary, i.e. pavement surface, a stationary thermal profile, i.e. 294.15 K, was imposed according to spot measurements performed on site indicating an almost constant temperature of the paving slab. Simulations were carried out by considering the average indoor air temperature experimentally measured within the cavity. A triangular mesh with refinements at the boundaries was implemented. The implemented models fully solve the Navier-Stokes equations, since no Boussinesq approximation was considered. Moreover, the K-epsilon Low-Reynolds model was applied to solve the turbulent flow regime inside the square cavity. After the numerical analysis, a validation of the simulation outputs was carried out for each scenario, assessed by comparing the results with the monitored data in terms of indoor temperature. The transient simulation was carried out with a 600-second time-step by using a two-variable group segregated solver and by considering an acceptable relative error of 10^{-5}.

5. Results and Discussion

5.1 Validation of the Model

After the implementation of the CFD model, preliminary validation was performed by using the experimental data available from continuous monitoring. Therefore, the simulation output and the collected data were compared in terms of air temperature. In particular, the air temperature values for the validation were extracted at a height of 1.4 m and almost at the center of the square cavity, in correspondence with the position of the temperature sensor. Fig. 3 shows the results of the validation procedure by highlighting the gap between the simulation output and the measurements. Globally, the elaborated model is shown to be sufficiently representative of the realistic thermal behavior of the prototype test-room case study building, since the simulated and experimental air temperature profiles are consistent with each other. However, a negligible and almost constant discrepancy of about 0.5 K on average between the simulated and measured indoor air temperature can be detected on a typical summer day. This indicates that the model slightly underestimates the indoor air temperature value, yet it is still valid and useful in relative terms for comparing the impact of cool envelope solutions applied over the case study building with the traditional one, which is the main objective of the present work.

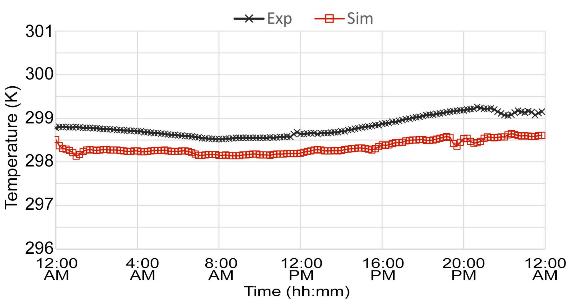

Fig. 3 – Validation of the CFD model against the experimental data available from the continuous monitoring of the main indoor/ outdoor microclimate parameters of the case study building

5.2 Indoor Thermal Environment

After the validation of the CFD model, the simulation of the indoor thermal field inside the square cavity was carried out, for both the standard and cool configuration of the case study building envelope. The results of the simulations are shown in Fig. 4.

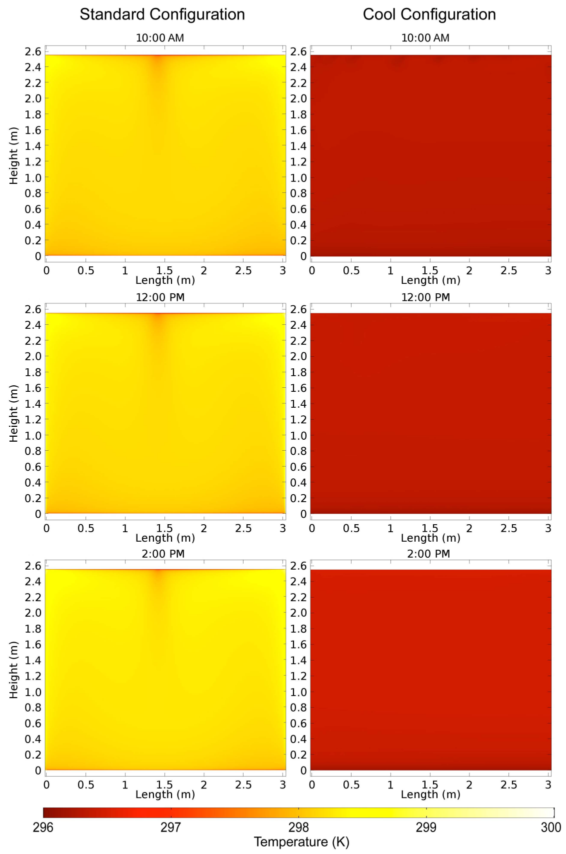

Fig. 4 – Indoor temperature distribution inside the square cavity in the standard and cool configurations at different times during the day, i.e. 10:00 am, 12:00 am, and 2:00 pm

In general, the temperature distribution inside the square cavity is almost always homogenous and fairly uniform in both the evaluated scenarios, i.e. standard and cool building envelope materials.

More in detail, when the standard configuration is considered, a quasi-defined thermal stratification can be detected, with a thermal-instability at the middle-top part of the cavity due to the effect of developing convective cells generated by the colder pavement. Therefore, the detected thermal gradient in the cavity is not completely defined due to the lower temperature of the North-facing wall and of the slab that causes a partially developed convective flow generating thermal instability. When the cool configuration is considered, on the other hand, the lower temperature difference between the different surface temperature profiles of the case study building causes a more stable temperature distribution. The square cavity is characterized by a well-established thermal stratification, causing a more uniform temperature distribution. By comparing the standard and cool scenarios, an almost constant temperature difference of about 2 K is always registered. Therefore, according to the simulations results, which are consistent with the experimental measurements performed, the application of highly-reflective materials on the building envelope is able to lower the indoor air temperature inside the square cavity compared to more traditional non-cool surface covering materials, by consequently improving the indoor thermal comfort inside the building.

5.3 Indoor Airflow Distribution

In this section, the results of the simulations of the indoor airflow conditions inside the case study square cavity are reported, for both the standard and cool configuration of the building envelope. Fig. 5 shows the indoor airflow distribution in the standard and cool scenarios at different hours during the day. From the results of the numerical analysis, a different indoor airflow distribution can be detected in the two configurations. In particular, in the standard scenario, two non-completely developed macro-convective cells can be identified, as a consequence of the huge temperature difference between the roof, the North and South wall surface temperatures. In the cool configuration, on the other hand, the reduced surface overheating caused by the highly reflective materials produces a reduced temperature difference between the considered temperature boundary conditions, and consequently a more stable airflow distribution.

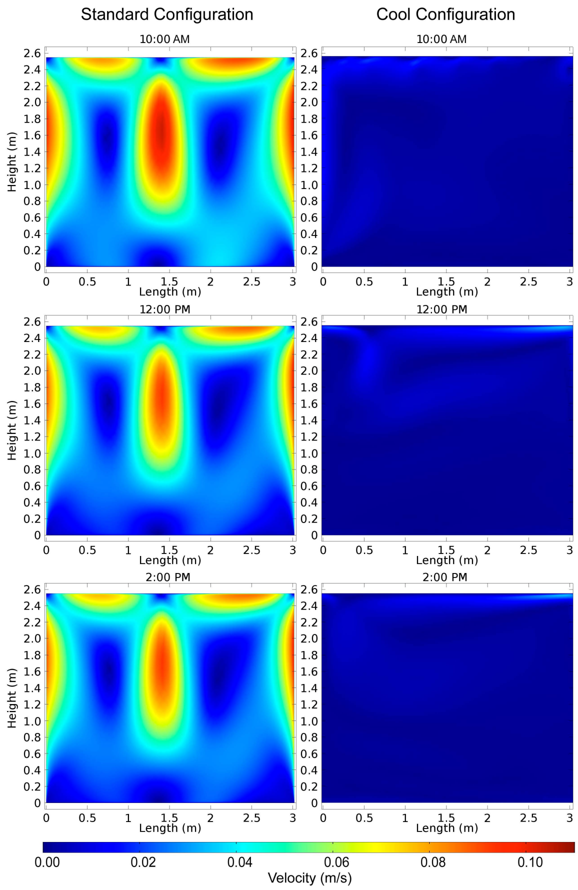

Fig. 5 – Indoor airflow distribution inside the square cavity in the standard and cool configurations at different times during the day, i.e. 10:00 am, 12:00 am, and 2:00 pm

6. Conclusion and Future Developments

The purpose of the present paper was to numerically predict the building indoor thermal environment and airflow distribution. To this aim, the calibrated CFD model of a case study prototype building, i.e. test-room, situated in central Italy, was elaborated, by considering the indoor heat transfer phenomena. In particular, the indoor thermal effect of the application of an innovative highly-reflective cool façade painting and cool roofing membrane compared to a more traditional "non-cool" envelope finishing is assessed. The results show that the implemented CFD model is able to accurately predict the realistic thermal behavior of the case study building. Therefore, the numerical analysis is detected to represent a suitable tool for predicting buildings thermal performance based on a few experimental data. According to the experimental campaign previously carried out, the results demonstrate that the application of cool envelope materials can significantly lower the indoor air temperature by consequently avoiding overheating risk, especially during extreme summer conditions. In particular, an average indoor air temperature reduction of 1.8 K is found in the cool scenario with respect to the standard one. Finally, the numerical analysis of the indoor airflow distribution shows that in the cool configuration a more stable airflow is generated compared to the standard scenario, where macro convective cells appear. This is motivated by the reduced temperature difference between the considered temperature boundary conditions generated by the highly reflective covering materials, that are able to maintain a lower surface temperature of the envelope components in the cool configuration of the square cavity. Future developments of the study will concern the numerical analysis of the indoor thermal field and airflow distribution in winter conditions.

Acknowledgement

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 657466 (INPATH-TES) and from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 678407 (ZERO-PLUS).

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